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16. ABSTRACT

Soil contamination often results from improper land disposal, storage, treatment, and spills of hazardous waste in liquid or solid form. In order to properly address the levels of pollutants up to which contaminated soil needs to be cleaned, it is necessary to estimate the magnitude of human exposure for each likely exposure pathway. The procedure developed in this paper for estimating the level of pollutant cleanup from soil relates to 1) identification of exposure pathways, 2) exposure assessment to estimate pollutant intakes by humans from each pathway, and 3) the use of health effects data to estimate the acceptable exposure levels.

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ESTIMATION OF MULTIMEDIA EXPOSURES RELATED TO HAZARDOUS WASTE FACILITIES

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INTRODUCTION

Soil contamination often results from improper land disposal, storage, treatment, and spills of hazardous waste in liquid or solid form. In order to properly address the levels of pollutants up to which contaminated soil needs to be cleaned, it is necessary to estimate the magnitude of human exposure for each likely exposure pathway. The procedure developed in this paper for estimating the level of pollutant cleanup from soil relates to 1) identification of exposure pathways, 2) exposure assessment to estimate pollutant intakes by humans from each pathway, and 3) the use of health effects data to estimate the acceptable exposure levels.

Dacre et al. (1980) presented an approach to predict preliminary pollutant limit values based on the use of equilibrium partitioning of a pollutant between environmental media. This approach will be inapplicable for some processes including, to name a few, rate of volatilization from soil, dispersion of air contaminants, and migration of leachate contaminants in the unsaturated and groundwater media, because they represent dynamic processes. In addition, these exposure pathways were addressed poorly or not at all by Dacre et al. (1980). However, it was concluded that the treatments represent a conceptual framework for examination of single exposure pathways, and only a beginning for examination of other critical areas.

Exposure assessment should include short-term and long-term periods of exposure, since acute as well as chronic health consequences need to be considered. Acute effects are normally noncancer effects, while chronic effects can relate to noncancer and oncogenic effects. Depending upon the circumstances under which human exposure occurs and the type of pollutant being considered, exhaustive exposure evaluation for all likely pathways may be avoided, with only the most controlling pathways included in the determination of acceptable contaminant cleanup level in soil.

This paper will present a method intended primarily to allow the estimation of permissible residual levels of contaminant associated with the cleanup of contaminated soils to meet acceptable health effects criteria. It can also be applicable to assessing the limits of pollutant that can be allowed in mixtures of soil and waste being landfilled.

After initial cleanup, the concentration profile in soil continues to change as time progresses, due to volatilization. This change in concentration results in changes in exposures. The transient volatilization rate is estimated by solving a partial differential equation which incorporates soil-air partition coefficient and diffusion. Exposures need to be averaged over the time period of concern, including short-term and long-term periods.

EXPOSURE PATHWAYS

Contaminants originally present in soil can be distributed in various environmental media. The soil leaching process is a major concern for groundwater contamination. Bioaccumulation in fish, in animals used for food, or in garden vegetables results from contaminated surface water or from contaminated soil on which animals graze or plants are grown. Volatile constituents in soil can be released into the atmosphere because their partial pressure in equilibrium with the concentrations in soil provides the driving force for diffusion along the soil column. Windblown

particulate matter can entrain toxic constituents into the air which people breathe. People can work in a garden where there is contaminated soil, and be subjected to dermal contact with pollutants that can be absorbed through the skin.

The presence of contaminants in environmental media being distributed from wastes disposed of in soil thus can pose a potential health risk to humans from the following sources of intake:

- Ingestion of contaminated soil;
- Inhalation of air containing contaminants in vapor or particulate form;
- Absorption of contaminants through the skin because of contact with contaminated soil;
- Drinking of contaminated water; and
- Ingestion of foods with equilibrated or bioaccumulated contaminants.

Other exposure pathways, such as phytotoxicity to plants, may also need to be considered.

Under normal conditions, significant soil ingestion is limited to children (Lepow, 1975). Although very limited information is available on the ranges of age subject to soil ingestion, one investigation presented a case study of an adult with a history of habitual eating of garden soil, which may have been associated with a pica illness (Wedeen et al., 1978). The fraction of soil contaminant absorbed by humans is dependent upon the type of compound and its soil contaminant adsorption characteristics, and is generally smaller than that which can be expected when contaminants are present in food or drinking water.

When exposure locations are distant from the contaminated site, dilution, biodegradation, dispersion, or chemical reactions may have a pronounced effect on exposures. Examples include dilution of contaminants by winds, dispersion in groundwater, and biodegradation in surface water. It is possible to incorporate such processes in exposure evaluations. The significance of exposures to inhaled or dermally-contacted contaminants

will also be dependent upon the absorption rate of such contaminants in the lungs or on human skin. The smaller the absorption rate, the less significant the exposure would be.

Once exposure pathways are identified, exposure evaluation requires information on the levels of concentration to which a given target population may be exposed. Each pathway may require route-specific evaluation, as described in the following sections.

ESTIMATION OF EXPOSURES RELATED TO CONTAMINATED SOIL

The combined human intake of contaminants from all exposure pathways should not exceed the acceptable intake (AI, in mg/day) needed for preventing adverse effects from short-term and lifetime exposures. Refer to the Nomenclature section for the meaning of symbols used. The intake from an individual route when soil is contaminated can be expressed quantitatively as follows:

i) Intake by soil ingestion (mg/day):

$$I_1 = (C_s)(IR \times 10^{-3})(GI)(SM)(F) \qquad (1)$$

The term $(C_s)(IR)$ in Eq. (1) represents the daily amount of a contaminant ingested resulting from soil ingestion, in μg/day, because C_s represents the contaminant concentration in soil (μg/g) and IR is the soil ingestion rate (g/day). The factor 10^{-3} is needed to convert the unit from μg/day to mg/day. The fraction of the ingested contaminants that will enter human organs and systems to cause toxicity is given as GI. If the contaminant undergoes biological or chemical degradation in soil, and follows first-order kinetics in its disappearance under isothermal conditions, the contaminant concentration will change as a function of time according to $C_o e^{-kt}$, where C_o is the initial contaminant concentration in soil. The concentration in soil will also be affected by transport processes, which

are incorporated in the individual pathway analysis. An individual may not always be present on the contaminated site over his lifetime. The frequency factor of exposure over a lifetime, SM, represents the fraction of a lifetime that an individual will be exposed to the contaminants under consideration. The factor F is necessary because soil ingestion only occurs during childhood (1 to 6 years of age), and the weight of the human body changes from childhood to adulthood.

ii) Intake by air inhalation of volatilized contaminants (mg/day):

$$I_2 = (K_{as})(C_s)(D)(IH \times 10^3)(ABA)(SM) \tag{2}$$

In Eq. (2), K_{as}, D, and IH represent the soil-air partition coefficient, the extent of dilution of the vapor concentration in equilibrium with the contaminant concentration on soil after being dispersed by winds in the atmosphere, and the average daily inhalation rate of ambient air, respectively. The term $(K_{as})(C_s)(D)(10^3)$ represents the ambient air concentration of a pollutant at the exposure location in mg/m^3 when K_{as} and C_s are given in g soil/cm^3 and mg/kg, respectively.

The determination of the ambient air concentration at an exposure location, $(K_{as})(C_s)(D)(10^3)$, or the dilution factor in the term, requires the estimation of transient emission rate, and the use of dispersion modeling. The emission rate will not only be transient, but it will also be retarded by soil or equivalent cover material. This phase of the problem requires solution of a partial differential equation, as described in the section entitled "Inhalation of Volatilized Contaminants."

iii) Intake by dermal absorption (mg/day):

$$I_3 = (C_s)(CR \times 10^{-3})(ABS)(SM) \tag{3}$$

There are many occasions when children playing in the yard or adults working in the garden will come in direct contact with contaminated soil. Dermal contact does not necessarily constitute adverse exposure. The contaminant needs to be systemic to be absorbed into the human body and to exert toxicity. In Eq. (3), the term $(C_s)(CR)$ represents the contaminant contact rate with skin in μg/day since C_s is in μg/g (=ppm) and CR is the dermal contact rate of soil in g/day. The factor 10^{-3} is used to convert the contact rate from μg/day to mg/day, and SM will be 1 when the short- or longer-term (10-day) exposure is estimated, and will be between 0 and 1 when the lifetime exposure is estimated.

iv) Intake by drinking water (mg/day):

$$I_4 = (C_w)(IW)(SM) \tag{4}$$

In Eq. (4) it is assumed that the contaminant in drinking water is completely absorbed into the human body at the average daily water consumption rate of IW or the absorption fraction is 1. In order to relate the contaminant concentration in groundwater, C_w, to the contaminant concentration in soil, C_s, a fate and transport model can be used to estimate the concentration in the leachate entering groundwater, or

$$C_w = C_L/f_g, \text{ mg/L} \tag{5}$$

where f_g represents a functional relationship describing contaminant transport in groundwater. This function should be selected to suit the most appropriate conditions for the system. The leachate concentration, C_L, referring to the contaminant concentration in liquids just before entering groundwater, should not be confused with the contaminant concentration in groundwater, which results from mixing of the leachate with groundwater. Also, care should be exercised in using groundwater transport models, be-

cause some models will treat the leachate concentration as a boundary condition, while others require the contaminant concentration in groundwater as a boundary condition, which should be obtained by groundwater monitoring. When the units of C_w and C_L are all in mg/L, then the function f_g becomes dimensionless. Most leachate from hazardous waste land disposal sites may enter groundwater over a finite surface area, favoring area source models for simulating pollutant transport in groundwater.

There is no reliable method of predicting the leachate concentration from the contaminant concentration in soil, or vice versa. For the exposure evaluation, an equilibrium relationship vetween soil and leachate will provide a first approximation. Monitoring data can also be used relating the concentrations between leachate and soil. An equilibrium condition can be written as

$$C_s = (K_{Ls})(C_L), \text{ mg/kg} \tag{6}$$

where K_{Ls} is a partition coefficient in (mg/kg)/(mg/L). Eqs. (4), (5), and (6) are combined to get

$$I_4 = \frac{C_s}{(f_g)(K_{LS})}(IW)(SM) \tag{7}$$

When the equilibrium condition is not appropriate, it can be modified to include transport processes between the soil and leachate.

v) Intake by fish ingestion (mg/day):

At the average daily fish consumption rate of IF (kg/day), and under the assumption of complete absorption of the contaminant associated with the consumption of fish, the exposure can be estimated as

$$I_5 = (C_F)(IF)(SM) \tag{8}$$

where C_p is the contaminant concentration in fish. The use of the bioconcentration factor BCF, (mg/kg fish)/(mg/L water), to relate pollutant concentrations in fish and water, gives

$$I_5 = (BCF)(C_w)(IF)(SM) \tag{9}$$

where it is assumed that contaminants are present in water in dissolved form and that bottom sediments or benthal deposits on which pollutants may be adsorbed are not directly swallowed by fish. Under the condition of equilibrium between the pollutant-containing soil and leachate which is generated from the soil, substitution of Eqs. (5) and (6) into Eq. (9) results in

$$I_5 = \frac{C_s}{(f_g)(K_{LS})}(BCF)(IF)(SM) \tag{10}$$

The transport functions, f_g, in Eqs. (7) and (10) may assume distinct mathematical descriptions, because one pertains to transport in groundwater and the other to that in surface water.

vi) Intake by inhalation of contaminants adsorbed on particulates (mg/day) may be expressed by

$$I_6 = (C_p)(IH)(C_s \times 10^{-9})(ABP)(SM) \tag{11}$$

Contaminant-containing soil can be airborne by blowing winds. In addition, toxic substances volatilized from contaminated soil can be adsorbed on particulate matter present in the ambient air. Exposure to contaminants occurs because of inhalation of air containing these particulates. The exposure location could be distant from the source of emission, or in the vicinity of the emission source. Exposure concentrations will change accordingly. Another form of exposure relates to inhalation of air con-

taining particulate matter on which volatile constituents are adsorbed. The intake rate can be estimated based on the concentration of contaminants in wind-dispersed soil or on particulate matter, C_s µg/g (=ppm), and the concentration of the particulates in the ambient air, C_p µg/m^3, as shown in Eq. (11). The absorption fraction, ABP, is used because contaminants present in or on soil (or particulate matter) may be bound on the solid material, reducing the contaminant's absorption rate. Finally, the factor 10^{-9} is a conversion factor to make the units consistent.

vii) Intake by ingestion of vegetables (mg/day):

The intake rate due to ingesting IV kg/day of vegetables, plants, or agricultural products containing C_v mg/L of contaminants will be

$$I_7 = (C_v)(IV)(SM) \tag{12}$$

If it is assumed that equilibrium is established between the contaminant concentrations in plant and soil, then the exposure can be modified as:

$$I_7 = (K_{sv})(C_s)(IV)(SM) \tag{13}$$

where K_{sv} is a partition coefficient defined as contaminant concentration in plant/total contaminant concentration in soil (mg/kg plant)/(mg/kg soil).

viii) Intake by ingestion of food meat:

The contaminant intake at consumption rate of IM (kg/day) of meat containing C_m (mg/kg) of pollutant is

$$I_8 = (C_m)(IM)(SM) \tag{14}$$

Here again, an equilibrium relationship is assumed between the contaminant concentrations in the animal body and plants. Therefore, the intake rate due to meat consumption is

$$I_8 = (K_{vm})(C_v)(IM)(SM)$$
$$= (K_{vm})(K_{sv})(C_s)(IM)(SM) \qquad (15)$$

where K_{vm} and K_{sv} are the partition coefficients used to describe pollutant distribution between meat and vegetables, and the partition between vegetables and soil, respectively.

Similar expressions can be written for other routes of exposure. In Eq. (4), it is assumed that the groundwater concentration of a pollutant at an exposure location can be determined (by using monitoring data or fate and transport models) from the knowledge of leachate concentration as given by a function f_g, and that the contaminated soil and its leachate are in equilibrium as given by $K_{LS} = C_s/C_L$. There are a number of functional relationships which can be used in place of f_g, as reviewed by Hwang (1984). Also, equilibrium relationships are assumed between fish and water for bioaccumulation, between soil and vegetables, and between food animals and plants consumed by the animals. In Eqs. (7), (10), (13), and (15), contaminants consumed by humans because they are present in drinking water, fish, and other food sources, are taken as completely absorbed by the human body. If data on the absorption rate for these pathways are available, such data should be used.

DETERMINATION OF PERMISSIBLE POLLUTANT LEVEL IN SOIL

The total intake from all possible exposure pathways is set equal to the acceptable intake (AI) for short-term and chronic health effects; or

$$AI = I_1 + I_2 + I_3 + \cdots \qquad (16)$$

Eq. (16) can be solved for permissible contaminant levels in soil corresponding to each acceptable intake. It is possible that some exposure pathways

occur independently of others. For example, a residence which is located on a contaminated site may use drinking water from a clean public water treatment system, and may thus be free of contaminants found on the site. It is also possible that domestic animals are not raised for food consumption on the contaminated site under consideration. Under such circumstances, all exposure pathways need not be considered. If exposure pathways of significant concern are related to soil ingestion, inhalation of contaminated air, or dermal contact with soil, Eqs. (1), (2), and (3) can be added to solve for C_s,

$$C_s = \frac{(AI)(1000)}{[(IR)(GI)(F) + (K_{as})(D)(IH)(ABA \times 10^6) + (CR)(ABS)]SM} \quad (17)$$

The emission rate is limited by the air phase concentration in equilibrium with the contaminant concentration in soil. Once the contaminant soil concentration reaches the level at which the vapor phase concentration in equilibrium with the soil is at the vapor pressure concentration, a further increase in contaminant concentration in soil ($C_s > C_{sm}$) does not increase the emission rate. At or above this concentration, the ambient air concentration remains constant regardless of the concentration of the contaminant in soil. Under such conditions, C_s in Eq. (2) is no longer a variable, and therefore Eq. (17) does not apply. This situation can be remedied by considering the intakes by the individual route of exposure at a constant value of C_s [$C_s = C_{sm}$ in Eq. (2)] for inhalation exposure, and solving for C_s. The form of the equation will be slightly different from that for Eq. (17).

$$C_s = \frac{(AI)(1000) - (K_{as})(C_{sm})(D)(IH \times 10^3)(ABA)(SM)}{[(IR)(GI)(F) + (CR)(ABS)]SM} \quad (18)$$

INCORPORATION OF TIME-VARYING PARAMETERS

The body weight of a human constantly changes until maturity. The calculation of AIs from the safe dose level (SL) given in mg/kg•day requires requires an assumption of body weight. For rigorous treatment, the estimation of lifetime exposure should take into account changes in body weight. In this case, it is convenient to work with SL instead of AI for exposure calculations. For carcinogens with a potency value at POT $(mg/kg \cdot day)^{-1}$, the equivalent SL at an assumed risk level, R (such as 10^{-6}, etc.), can be obtained by

$$(SL)eq. = \frac{R}{POT}, \ mg/kg \cdot day$$

The risk level shown represents an upper-bound estimate. An upper-bound estimate of risk of 10^{-6}, for example, means that upon lifetime exposure to a contaminant, a person experiences an increased maximum risk of developing cancer in a probability of 1 in one million.

Snyder (1975) presented data on the change of body weight as a function of age. A regression analysis on Snyder's data for average male weight provides the following relationship.

$$BW = 3.14 + 3.52 \ (age), \ kg \text{ for age } 0 - 18 \text{ yr} \qquad (19)$$

$$BW = 70, \ kg \text{ for age greater than } 18 \text{ yr} \qquad (20)$$

To obtain the daily exposure averaged over an individual's lifetime, intake rates given by Eqs. (1) - (3), (7), (10), (11), (13), and (15) should be divided by the body weight, and the daily intake per unit body weight should be averaged by summing the total intake per unit body weight over the period during which exposure occurs and dividing the result by LT. For purposes of illustration, Eqs. (1) and (2) are repeated below:

i) The average daily exposure by soil ingestion per unit body weight in mg/kg·day can be determined as

$$\frac{I_1}{BW} = \sum_{1\ day}^{25550\ days} \frac{(C_o e^{-kt})(IR \times 10^3)(GI)(SM)}{(BW)(LT)} \qquad (21)$$

Again, in Eq. (21) [also in in Eq. (22)], the contaminant present in soil is assumed to disappear by biodegradation and other reactions, according to first-order kinetics. Other processes affecting the concentration in soil are considered in the exposure analyses for individual pathways.

ii) The average daily exposure by inhalation of volatilized contaminants in mg/kg·day is calculated from

$$\frac{I_2}{BW} = \sum_{1\ day}^{25550\ days} \frac{(K_{as})(C_o e^{-kt})(D)(IH \times 10^3)(ABA)(SM)}{(BW)(LT)} \qquad (22)$$

Similar expressions can be written for other exposure pathways. For conservative contaminants, the term $C_o e^{-kt}$ in Eqs. (21) and (22) can be replaced by C_s. The total dose from all exposures should not exceed SL, or $(SL)_{eq.}$

$$SL = \frac{I_1}{BW} + \frac{I_2}{BW} + \frac{I_3}{BW} + \ldots \qquad \text{for noncarcinogenic effects} \qquad (23)$$

$$(SL)_{eq.} = \frac{I_1}{BW} + \frac{I_2}{BW} + \frac{I_3}{BW} + \qquad \text{for carcinogenic effects} \qquad (24)$$

As before, Eq. (23) or (24) can be solved for the permissible concentrations in soil, C_s. From Eqs. (1) and (21), one can solve for the factor F for use in Eq. (1). The use of LT = 25550 days, and the assumption that soil ingestion occurs during ages 1 through 5 (t = 365 to 1825 days),

yield F = 0.323. The factor F does not depend on the soil ingestion rate. Eqs. (1) and (21) use Eqs. (20) and (19), respectively, for BW.

INHALATION OF VOLATILIZED CONTAMINANTS

Exposure occurs at or near contaminated sites through inhalation of ambient air contaminated with toxic vapors or particulate matter on which a contaminant is absorbed. Volatile constitutents emitted from contaminated soil will be diluted by the action of winds before a person inhales the ambient air. When a contaminant is adsorbed on soil, the vapor pressure of the contaminant above the soil surface will be always smaller than the pure component vapor pressure. In other words, the adsorption phenomenon depresses the vapor pressure that can exist under saturated conditions. When adsorption reaches its saturation capacity on soil, the partial pressure will be equal to the pure component vapor pressure.

In calculating ambient air concentrations of contaminants, the first task is to estimate emission rates from the bulk of soil contaminated at various concentrations. The emission rate calculations for steady-state conditions can be performed using the methods presented by Farmer et al. (1980), and subsequently summarized by Hwang (1982). Thibodeaux and Hwang (1982) presented the transient emission rate from land treated facilities. A new mathematical treatment is needed to estimate transient rates of emissions from contaminated soil. The transient emission rate is obtained by solving a partial differential equation based on a material balance around the soil column, as described in this section.

A mass balance over an infinitesimal vertical element of soil for vapor phase diffusion and soil phase adsorption can be written as follows (Hwang, 1985):

$$\frac{\partial C}{\partial t} + \bar{\rho}_s \frac{\partial C_s}{\partial t} = \frac{\partial}{\partial z} \left(\varepsilon D_{ei} \frac{\partial C}{\partial z} \right) \qquad (25)$$

Since changes in soil and vapor phase concentrations of contaminants occur slowly, it can be assumed that the vapor phase and soil-solid phase concentrations of a contaminant are in local equilibrium. The contaminant concentrations in soil and in interstitial vapors are assumed to be at equilibrium, and they are related by the following equation:

$$C_s = \frac{K_d}{41\ H} C \tag{26}$$

where the conversion factor 41 is needed for consistency of the units given in the Nomenclature.

Rearranging Eq. (25) and substituting Eq. (26) into the resulting relationship yields

$$D_{ei} \frac{\partial^2 C}{\partial z^2} = \left(1 + \frac{(\bar{\rho}_s)(K_d)}{(\varepsilon)(H)}\right) \frac{\partial C}{\partial t} \tag{27}$$

or

$$\alpha \frac{\partial^2 C}{\partial z^2} = \frac{\partial C}{\partial t} \tag{28}$$

where

$$\alpha = \frac{(D_{ei})(\varepsilon)}{[\varepsilon + (\rho_s)(1-\varepsilon)(K_d)/H]} \tag{29}$$

α can also be defined as

$$\alpha = \frac{D_{ei}}{1 + (K)(S)} \tag{30}$$

where

$$K = \frac{K_d}{H} \rho_s$$

$$S = (1-\varepsilon)/\varepsilon$$

Eq. (27) can be solved to estimate contaminant concentration in soil-solids, vapor phase concentration, and emission rate into air above soil for the following two cases:

Case 1. Surface is exposed to the atmosphere. The initial and boundary conditions are

1. I.C. $C = (H/K_d)C_{SO}$, at $t=0$, $z>=0$
2. B.C. $C = (H/K_d)C_{SO}$, at $z=\infty$, $t>0$
3. B.C. $C = 0$, at $z=0$, $t>0$

where C_{SO} is the initial concentration of contaminant in soil. The solution to Eq. (27) for the above initial and boundary conditions is (Crank, 1985)

$$C = (H/K_d)C_{SO} \cdot \text{erf}\left(\frac{z}{2\sqrt{\alpha t}}\right) \tag{31}$$

where

$$\text{erf}(n) = \text{error function} = \frac{2}{\sqrt{\pi}} \int_0^n \exp(-n^2)dn$$

The flux rate at the soil-air interface (N_A) can be estimated as a function of time from Eq. (31) by using the concentration gradient as follows:

$$N_A = -(\varepsilon)(D_{ei}) \left.\frac{\partial C}{\partial z}\right|_{z=o} = \frac{(\varepsilon)(D_{ei})(\frac{H}{K_d})(C_{SO})}{\sqrt{\pi \alpha t}} \tag{32}$$

The average flux rate, N_A, over an exposure interval, T, is calculated by time-averaging Eq. (32) to yield

$$\bar{N}_A(T) = 2\, N_A(T) \tag{33}$$

The total average emission rate, Q, can be calculated from

$$Q = (A)(\bar{N}_A) \tag{34}$$

Case 2. The contaminated surface is covered with contaminant-free soil material. Let ℓ = thickness of cover (cm), and L = the depth of contamination measured from the top of cover material (cm). The initial and boundary conditions become:

1. I.C. $C = 0$, $0 \leq z \leq \ell$, at $t = 0$
2. I.C. $C = C_o$ $\ell < z \leq L$, at $t = 0$
3. B.C. $C = 0$, $z = 0$, at $t > 0$
4. B.C. $\frac{\partial C}{\partial z} = 0$, $z = L$, at $t > 0$

where C_o is the initial contaminant concentration in the vapor phase in equilibrium with the solid phase [$C_o = (H/K_d)C_{SO}$]. Eq. (27), with these initial and boundary conditions, can be solved using the Fourier Series techniques. The solution is (Crank, 1985)

$$C = \frac{4C_o}{\pi} \sum_{n=0}^{\infty} e^{-\frac{\alpha(2n+1)^2\, \pi^2 t}{4 \cdot L^2}} \cdot \sin\left[\frac{(2n+1)}{2}\frac{\pi z}{L}\right] \cos\left[\frac{(2n+1)}{2}\frac{\pi \ell}{L}\right] \tag{35}$$

The flux rate at the soil-air interface (N_A) can be estimated as a function of time from Eq. (35).

$$N_A = \varepsilon D_{ei} \left.\frac{\partial C}{\partial z}\right|_{z=0} = \frac{2C_o \varepsilon D_{ei}}{L} \sum_{n=0}^{\infty} e^{-\frac{\alpha(2n+1)^2 \pi^2 t}{4 \cdot L^2}} \cos\left[\frac{(2n+1)}{2} \frac{\pi \ell}{L}\right] \tag{36}$$

The average emission rate over a time period, T, can be obtained by integrating Eq. (36). The result is

$$\bar{N}_A = \frac{8(H/K_d)(C_{SO})(\varepsilon)(D_{ei})(L)}{\alpha \pi^2 T} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \left[e^{-\frac{\alpha(2n+1)^2 \pi^2 t_1}{4 \cdot L^2}} - e^{-\frac{\alpha(2n+1)^2 \pi^2 t_2}{4 \cdot L^2}}\right] \cdot \cos\left[\frac{(2n+1)}{2} \frac{\pi \ell}{L}\right] \tag{37}$$

The time interval $t_2 - t_1$ in Eq. (37) represents the exposure interval. It should be noted that when the value of the expression $\frac{\alpha(2n+1)^2 \pi^2}{4L^2}$ in the exponential term of Eq. (37) is small or considerably less than 1, the average of the exponential term over a time, t, will be close to 1. In this situation, averaging of the exponential term of Eq. (36) by the integration formulae given by Eq. (37) may easily result in an erroneous answer because one has to evaluate very precise numbers of many decimal points for the values of the exponential term. It is more practical to numerically average Eq. (36) than to obtain the average value by using the integration formulae given by Eq. (37):

$$\bar{N}_A = \frac{2(H/K_d)C_{SO}(\varepsilon)(D_{ei})}{L} \frac{1}{T} \sum_{n=0}^{\infty} \left[\int_{t_1}^{t_2} e^{\left(-\frac{\alpha(2n+1)^2 \pi^2}{4 \cdot L^2}\right)}\right] dt \cdot \cos\left[\frac{(2n+1)}{2} \frac{\pi \ell}{L}\right] \tag{38}$$

Dispersion models (Bruce, 1969; Wark and Warner, 1981) estimate the ambient air concentrations to which populations may be exposed on a daily or annual basis. While these dispersion models can be used, at any distance x from the site, to estimate ambient air concentrations, they cannot be used on-site. On-site ambient air concentrations can be estimated using the following equation:

$$C_a = \frac{Q}{(LS)(V)(MH)} \tag{39}$$

The dilution factor needed in using Eq. (2) or (17) can be obtained by:

$$D = C_a/C_{as} \tag{40}$$

The value of C_{as} increases continuously as the contaminant concentration in soil increases, until the concentration of contaminant in the air phase corresponds to that of contaminant vapor pressure. Once the condition of vapor saturation is reached, a further increase in contaminant concentration in soil will have a minimal effect on the volatilization rate.

VALUES FOR EXPOSURE ASSESSMENT PARAMETERS

Soil Ingestion

Limited information is available on the likely rate of soil ingestion by children and adults. The situations from which the information is derived differ from study to study. Lepow et al. (1975) studied the mouthing behavior of ten 2- to 6-year-old children in connection with investigations into the principal cause for the excessive lead accumulation observed in the children. The total soil ingestion rate for a 2-year-old child, based on the average amount of street dirt, house dust, and soil ingested by the child as a result of putting his hands and fingers in his mouth, can be summed as 0.6 g of soil per day.

Using the levels of blood lead concentration and the concentration of lead in the soil analyzed, Wedeen et al. (1978) estimated the amount of lead a woman had habitually consumed each year from her garden soil. Based on this estimate, the soil ingestion rate is estimated to have been between 1.96 and 3.9 g/day, with an average value of about 3 g/day. The lead concentration in the dried garden soil was reported to be between 690 and 700 micrograms per gram of soil.

Investigators at the Centers for Disease Control (CDC) presented lifetime rates of ingestion of contaminated soil according to age group (Kimbrough et al., 1984), and for children used in the experimental soil ingestion study (Binder, 1985). The Kimbrough et al. paper stated that the data presented was "based on work done studying lead uptake from contaminated soils." The ingestion rate was assumed to change at different ages, and was given as 0 for age group 0 to 9 months, as 1 g/day for age group 9 to 18 months, as 10 g/day for age group 1.5 to 3.5 years, as 1 g/day for age group 3.5 to 5 years, and as 0.1 g/day for a 5-year-old child. Experiments reported by Binder dealt with children between the ages of 1 to 5 years, living in East Helena, Montana, and analyzed the feces of the children for silica, aluminum, and titanium. Back-calculation of the soil ingestion rates using the analytical results showed the ingestion rate to be in the range of 0.12 to 1.8 g/day of soil. The lower numbers are based on the analysis of silica and aluminum, while the higher numbers were obtained from the titanium results. No definitive explanation was provided regarding the discrepancies in the results based on silica, aluminum, or titanium.

Dermal Contact with Soil

Deposition of contaminated soil, dirt, or dust on human skin can provide another pathway for human intake of contaminants. These contaminants can be absorbed through human skin when contaminated particulates come

into contact with the skin. Exposure evaluation requires an estimation of the amount of the particulates on skin, and the extent or rate of absorption (which will be dependent upon the type of chemicals involved; some chemicals are readily absorbed, while others are not).

Many factors may affect the amount of soil that can be accumulated on human skin. Such factors include the size of the exposed skin area, contact time, type of soil, soil conditions, and type of activity in which the exposed individual was engaged (e.g., the amount of soil deposited on the skin of children playing in a contaminated area is likely to differ from that deposited on on the skin of adults working in a garden).

Lepow (1975) and Roels et al. (1980), using adhesive tape, measured the amount of soil and dirt accumulated by children on exposed areas such as hands, palms, and fingers. The measured amounts of soil ranged from 0.5 to 1.5 mg/cm^2, with an average value of 1 mg/cm^2. It should be noted that this is an average value over the surface of the exposure area, and that some parts of the body may have more accumulation of soil than others. The exposed surface area of an adult is estimated to range from about 900 to 2,900 cm^2.

The variability of the factors mentioned above makes it difficult to arrive at an average value for the amount of soil and dirt accumulated on skin. Assumptions of (1) an average soil deposition of 1 mg/cm^2, and (2) an exposed surface area of about 1,000 cm^2, provide an average daily deposition rate of 1 g/day (within a variability range as high as a factor of two) (U.S. EPA, 1984).

Investigators at the CDC estimated the amounts of daily deposition of soil on skin according to age group. Their estimates indicate that the daily amount of soil deposited on skin is 0 for age group 0 to 9 months; 1 g for age group 9 to 18 months; 10 g for age group 1.5 to 3.5 years; 1 g for age group 3.5 15 years; and 100 mg at age 15 years (Kimbrough et al., 1984).

Transport of Groundwater Contaminants

Contaminated leachate will impact groundwater quality. The area-source groundwater model (Hwang, 1985), among others referred to in the references, can be used to estimate the extent of a contaminant's retardation, dispersion, and dilution in the groundwater medium. The precipitation rate is needed to estimate the leachate generation rate, which becomes a source term in the groundwater fate and transport model. The retardation factor will affect the time of pollutant travel.

The groundwater transport analysis can also be used to back-calculate leachate concentrations entering groundwater below a hazardous waste facility, based on allowable concentrations at a compliance point. This functional relationship is substituted in Eq. (4) for use in estimating the permissible concentration in soil. Also, the soil-water partition coefficient is needed under the assumption that equilibrium is established between the contaminants in soil and leachate.

Other Routes of Exposure

Exposure to contaminants may occur when people eat vegetables grown on contaminated soil, animals that have grazed in contaminated pasture or wildlands, or fish from contaminated waters; or when people breathe particulate matter on which contaminants are adsorbed. Since the concentration of a contaminant in soil eventually affects its concentration in food material, the use of Eqs. (10), (13), and (15) requires a partition coefficient that describes the chemical equilibrium between the soil and equilibrating food material. The use of Eq. (11) for estimating exposure from particulate inhalation requires information on the concentration of wind-blown particulate matter in the air. It can be noted that the Federal primary ambient air quality standard for particulate matter is 75 $\mu g/m^3$.

It is difficult to estimate the chemical equilibrium partitioning between the soil and plants, and between plants and animals, although the bioaccumulation factor can be estimated from data on the octanol-water

partition coefficient (Veith, 1980). The extent of plant uptake of a chemical, and its distribution in animals, will depend on the type of chemical, the type of plant, and the texture of the soil in which the plant is grown. Plant uptake is generally small in the case of many organic chemicals. The values of K_{sv} for dieldrin, for example, range from 0.03 to 0.67. The lower value is for cotton hay and cucumbers grown in silt loam and Si-Cl loam, and the higher value is for soybean hay grown in sandy loam (Nash et al., 1970).

Values for other pertinent parameters needed in the multimedia exposure assessment are listed in Table 1.

Table 1. Parameter Values Used in Exposure Evaluation

Body weight[a]:	Adult	70 kg
	Child	10 kg
Lifetime:		70 years
Soil ingestion rate:	ica, t pi	3 g/day with p ages 1-6 0.6 g/day withouca, ages 1-6
l rmal contact rate of soil:		1 g/day
Dai y consumption rate:		
Fish		0.0065 kg/day
Vegetables		0.01 kg/day
Meat		0.63 kg/day
Air inhalation rate:	Adult	20 m^3/day
	Child	10 m^3/day
Water ingestion rate:	Adult	2 L/day
	Child	1 L/day

[a]Average values.

A CASE STUDY FOR PCBs CLEANUP LEVELS

The method described above is applied to develop advisory levels for polychlorinated biphenyls cleanup, in order to protect public health from short-term and long-term exposures. Exposure pathways considered in developing the advisories include drinking water, ingestion of PCB-contaminated soil by children and adults, inhalation of ambient air, and dermal contact. Other exposure routes, such as food intake and ingestion of fish which have bioaccumulated PCBs, are considered to the extent that these pathways constitute relatively important exposure routes.

In view of the high bioaccumulation factor for PCBs, the consideration of bioaccumulation is important in setting permissible PCB levels in surface water in which aquatic animals live, or its bottom sediments. If one of these routes is a controlling factor in relation to the exposure route or human intake considered, the advisory levels presented here need to be reevaluated.

The short-term acceptable intakes derived from animal studies for noncarcinogenic effects can be used to establish permissible levels of PCBs for short-term exposure. However, this AI value will not be shown for illustration in this paper. The permissible PCB concentrations in soil for each carcinogenic risk level from 10^{-5} to 10^{-7} are based on the potency factor of 4 $(mg/kg \cdot day)^{-1}$, rounded off from two separate evaluations reported for PCB-1260. As an example, the average daily dose rate corresponding to 10^{-6} risk can be calculated from the potency slope as 1.75×10^{-5} mg/day.

CHEMICAL AND PHYSICAL PROPERTIES OF PCBs EVALUATED

Commercial-grade PCBs marketed as Aroclors in the United States are mixtures of many chlorinated biphenyl compounds in various proportions. Each PCB compound may exhibit its own toxicological characteristics and physical and chemical properties. These facts complicate the exposure analysis and the subsequent estimation of the allowable concentrations in

drinking water and soil. It is likely that chemical and physical properties reported in the literature for each Aroclor designation represent an average property for the mixture. To define the variability of safe levels for contamination by different Aroclor designations, exposure analyses have been performed for several Aroclors: Aroclor 1242, 1248, 1254, and 1260. Pertinent chemical and physical properties for these Aroclors are shown in Table 2.

The widespread distribution of PCBs in the environment suggests that PCBs are transported from treatment, storage, and disposal facilities through the atmosphere in the vapor and adsorbed form on particulate matter. Soil contaminated with PCBs will exert vapor pressure for volatilization.

TABLE 2. Chemical and Physical Properties of Aroclors Evaluated

	PCB-1242	PCB-1248	PCB-1254	PCB-1260
Molecular weight	266.5	299.5	328.4	377.5
K_{ow}	380,000	1,300,000	1,070,000	14,000,000
Specific gravity	1.38	1.445	1.538	1.62
Solubility in water (mg/L)	0.24	5.4×10^{-2}	1.2×10^{-2} - 0.03	2.7×10^{-3}
Vapor pressure (mmHg) at 25°C	4.06×10^{-4}	4.94×10^{-4}	7.71×10^{-5}	4.05×10^{-5}
Henry's Law constant ($atm \cdot m^3/g$ mol)	5.73×10^{-4}	3.51×10^{-3}	8.37×10^{-3}	7.13×10^{-3}
Bioaccumulation factor 31,200 L/kg				
Soil-water partition coefficient 40-1000 L/kg (U.S. EPA, 1980)				

Experimental data (U.S. EPA, 1980) suggest that PCBs are strongly adsorbed on earth materials, including soil. PCBs adsorbed on soil, or present in mixture with soil, will be subject to ingestion if the contaminated sites are accessible to children or adults with habitual pica. The reported values for the soil-water partition coefficient, K_d, range from 1000 cm^3 water/g soil for clay material to 40 cm^3 water/g soil for sandy material.

EXAMPLE CALCULATIONS

Unsteady-State Emission Rate from Contaminated Soil with No Cover

In this example, soil contaminated with PCB-1254 is assumed to be exposed to the atmosphere in the absence of a cover. The average emission rate is obtained by averaging the instantaneous emission rate over a time period, t (sec), using Eq. (33). For $D_i = 0.05\ cm^2/s$, $\varepsilon = 0.35$, and $K_d = 1000\ cm^3$ water/g soil:

$$D_{ei} = 0.05\ (0.35)^{1/3} = 0.0352\ cm^2/s$$

$$\frac{H}{K_d} \text{ in } \frac{g\ soil}{cm^3\ air} = \frac{8.37 \times 10^{-3}}{1000} \times 41 = 0.000343\ \frac{mg/cm^3\ air}{mg/g\ soil}$$

Hence,

$$\alpha = \frac{0.023}{0.35 + 2.65(0.65)\ \frac{1}{0.000343}} = 2.45 \times 10^{-6}\ cm^2/s$$

The average emission rate when the initial concentration in soil is $C_{SO} = 10^{-6}$ g/g (= 1 ppm), can be obtained by averaging over 70 years:

- 70 years (= 2.2075 x 10^9 sec) average:

$$\bar{N}_A = 0.00034(0.35)\ \frac{2(0.0352)(10^{-6})}{3.14(2.45\times10^{-6})(2.2075\times10^{9})}$$

$$= 6.4 \times 10^{-14}\ g/cm^2 \cdot s$$

Although the cleanup level is initially unknown, solution of Eq. (2) or (17) for C_s does not require trial and error calculations, because the dilution factor can be calculated independent of the contaminant concentration in soil in the absence of a cover material.

Unsteady-State Emission from Contaminated Soil with Soil Cover Applied

In this example, clean soil is applied on top of the contaminated soil surface. Emissions will occur through the cover material, and will remain unsteady below the vapor saturation point. The average emission rate, under the assumption of an initial contamination depth of L=200 cm, can be obtained using Eq. (38). The average emission over a period of 70 years (2.2075 x 10^9 sec) can be obtained as:

$$\bar{N}_A = 5 \times 10^{-14}\ g/cm^2 \cdot s$$

When the clean cover material is applied on top of the cleaned or spill site, the solution of Eq. (2) or (17) for C_s requires an initial estimate for C_s, and a trial-and-error calculation.

An Example of the Air Dilution Factor Calculation

This example illustrates the method of calculating the air dilution factor needed in the exposure analysis. The emission rates are used as input in applying dispersion modeling to obtain the ambient air concentration, C_a, downstream of the site. An average wind speed of 10 mph (=4.47 m/s) is used in this exposure evaluation. The on-site ambient air concen-

tration is calculated using Eq. (41). For the 70-year average emission rate without cover, calculated above, the onsite air concentration for a 0.5-acre site can be obtained as follows:

$$C_a = \frac{6.4\times10^{-14}\times10^{6}(0.5)(4.047\times10^{7})}{45(4.47)(0.5)(2)} = 6.4 \times 10^{-3}\ \mu g/m^3$$

The vapor phase concentration of PCB being emitted from the soil surface is assumed to be in equilibrium with the assumed soil PCB concentration (1 ppm = 1 µg/g). This vapor phase concentration, before being mixed with air, is:

$$C_{as} = \frac{H}{K_d}(41)\ C_s = 0.000343\ g\ soil/cm^3 \cdot (10^6 cm^3/m^3) \cdot 1\ \mu g/g$$

$$= 343\ \mu g/m^3$$

Hence, the dilution factor, D, for the on-site ambient air becomes

$$D = 6.4 \times 10^{-3}/343 = 1.87 \times 10^{-5}$$

The concentration of PCBs in soil corresponding to the saturation point can be estimated from the knowledge of vapor pressure and air-soil partitioning. For example, since the vapor pressure of Aroclor-1254 (7.71×10^{-5} mmHg) corresponds to the saturation concentration, C_{as}, of 1,372.7 $\mu g/m^3$, the PCB concentration in soil at the saturation point is:

$$C_{sm} = \frac{1{,}362.7\ \mu g/m^3}{[K_{as}(g\ soil/cm^3\ air) \times 10^6\ cm^3/m^3]}$$

$$= 1{,}362.7/(0.000343\times10^6) = 4\ \mu g/g$$

for a value for K_d of 1,000 cm^3/g used in this example. The saturation concentration is dependent upon the value of the air-soil partition coefficient. The concentration of PCBs in saturated vapor and the corresponding PCB concentrations in soil are calculated for K_d=1000 and 40 cm^3/g. Table 3 lists the calculated values. Since the PCB concentration in vapor phase cannot exceed the saturation concentration, the values of C_s in Eq. (2) or (17) cannot exceed the maximum value, C_{sm}.

Table 3. Concentration of PCBs in Soil at Saturation Vapor Pressure at Two K_d Values

	PCB soil concentration in equil. with saturated vapor (ppm)		Saturated vapor concentration ($\mu g/m^3$)
	K =1000	K =40	
Aroclor-1242	250	10	5823.3
Aroclor-1248	55.3	2.2	7962.8
Aroclor-1254	4	0.16	1362.7
Aroclor-1260	28.2	1.13	822.8

RESULTS OF EXAMPLE CALCULATIONS

For exposure pathways by soil ingestion, vapor inhalation, and dermal contact with soil, Eq. (17) is applied to solve for C_s corresponding to the lifetime cancer risk dose at 10^{-6} risk:

$$C_s = \frac{1.75 \times 10^{-5} \times 1000}{[0.6(0.3)(0.323)+0.000343(1.87\times10^{-5})(20)(0.5)(10^6)+(1)(0.05)]0.5}$$

$$= 0.2 \text{ ppm}$$

This value of C_s should be reused to calculate a new value for C_s, which is also found to be 0.2 ppm. The results of the calculations are given in Table 4. In these calculations, it is assumed that GI = 0.3, ABA = 0.5, ABS = 0.05, and SM = 0.5. For short-term exposure calculations, the value for SM = 1 can be assumed, meaning that the frequency of presence on-site for a given day is 1. The results of the long-term exposure evaluation for carcinogenic effects are also given in Table 4 for risk values ranging from 10^{-5} to 10^{-7}. It should be remembered that Table 4 is prepared for PCB-1254 at K_d = 1000. The permissible levels are evaluated at two different rates of soil ingestion. Calculations show that at a particulate concentration of 75 $\mu g/m^3$, the PCB intake by inhalation of particulate matter at contaminated sites is relatively unimportant. Hence, the route of exposure by inhalation of particulates in the ambient air is not considered in the example calculation for PCBs.

When all four Aroclors and the upper and lower values of K_d (1000 and 40) are considered, the permissible levels can be summarized as ranges within which a permissible level of PCB cleanup should lie. These ranges reflect the different Henry's Law constant for each Aroclor in addition to the water-soil partition coefficient, and are shown in Table 5. The symbol, VS, indicates that the emission occurs at vapor saturation conditions, and hence no upper bound limit of PCB concentration for inhalation exposure can be determined. It is assumed that at a distance of 0.1 km from the site, the exposure occurs through inhalation only.

Similar calculations were performed under the scenario that the site is covered with clean soil material or its equivalent after cleanup. The normal detection range for PCB analysis is considered to be in the range of 0.05 to 0.1 ppm, below which the soil will be considered clean. The results of these calculations are shown in Table 6 for PCB-1254 at K_d=1000. The effect of cover material would be to retard the emission rate and to reduce the effective concentration of PCBs in the soil.

Table 4. PCB-1254 Levels in Soil Corresponding to AIs with no Cover Material (PPM)

	Lifetime intake level 0.00175 (10^{-7} risk)	0.0175 (10^{-6} risk)	0.175 (10^{-5} risk)
Soil ingestion[a] Dermal contact Inhalation	0.01	0.1	1
Soil ingestion[b] Dermal contact Inhalation	0.02	0.2	2
On-site inhalation only	0.05	0.5	7
0.1 km from site	7	VS	VS

[a]Children ages 1-6, with pica, consuming 3 g soil/day.
[b]Children ages 1-6, without pica, consuming 0.6 g soil/day.
[c]Soil-air participation coefficient=3.43×10^{-4} g/cm^3 at K_d=1000.

Table 5. Levels of Evaluated PCBs in Soil Corresponding to AIs with no Cover (PPM)

	Lifetime intake level 0.00175 (10^{-7} risk)	0.0175 (10^{-6} risk)	0.175 (10^{-5} risk)
Soil ingestion[a] Dermal contact Inhalation	0.008-0.01	0.08-0.1	0.8-2
Soil ingestion[b] Dermal contact Inhalation	0.01-0.06	0.1-0.6	1-6
On-site inhalation only	0.01-0.2	0.1-2.0	1-20
0.1 km from site	2-220	90-VS	VS

[a]Children ages 1-6, with pica, consuming 3 g soil/day.
[b]Children ages 1-6, without pica, consuming 0.6 g soil/day.

Table 6. PCB-1254 Levels in Soil Corresponding to AIs with 10-Inch Clean Soil Cover

	Lifetime intake level		
	0.00175	0.0175	0.175
	(10^{-7} risk)	(10^{-6} risk)	(10^{-5} risk)
Soil ingestion[a] Dermal contact Inhalation	0.02	0.2	2
Soil ingestion[b] Dermal contact Inhalation	0.03	0.3	4
On-site inhalation only	0.08	0.8	14
0.1 km from site	14	VS	VS

[a]Children ages 1-6, with pica, consuming 3 g soil/day.
[b]Children ages 1-6, without pica, consuming 0.6 g soil/day.
[c]Soil-air partition coefficient=3.43×10^{-4} g/cm^3 at K_d=1000.

DISCUSSION

Except for the calculations pertaining to estimation of emission rate and dispersion modeling, the method presented is straightforward in estimating multimedia exposures for use in determining cleanup levels of contaminants in soil.

There are uncertainties associated with input parameters in estimating exposures. Although the ranges of values for permissible cleanup levels have been obtained for PCB examples without defining uncertainty limits, site-specific evaluations can narrow the confidence intervals.

Recent experimental investigations show that the capillary effect may play a role in controlling the volatile emission rate when cover material is applied (DuPont, 1985). The data indicate that, for certain land-spread chemicals, the emission rate increases rather than decreases as time elapses, as predicted by solving for Fick's law of diffusion. The liquid waste initially spread on land and covered by soil will exert capillary tension

in the dry zone of cover material, and will slowly rise toward the soil surface. This is suspected to be the cause of the increasing emission rate at a longer elapsed time than at the beginning of the initial cover-up. The increased emission will have an effect on lowering permissible levels of contaminants in soil when inhalation exposures are significant. The degree of liquid saturation to produce this "wicking" effect, if any, is unknown.

In case study examples for PCBs, it is assumed that the 10-inch clean cover material used remains undisturbed by human activities on the site. At times this assumption may be arbitrary, because an opportunity could exist that would place the contaminated soil surface in contact with the atmosphere because of inadvertent disturbances of soil surfaces, construction activities, utility installation, precipitation, or the activities of children playing on the site, to name a few. Such contingencies will require additional thickness of cover material, or, alternatively, the site should be made inaccessible to children or should be kept free of any activities that would lead to disturbances of the soil surfaces. Spills on top of the clean cover will result in a situation equivalent to the surface contamination case, requiring a more stringent concentration limit in soil. In such cases, the results given for the 10-inch thick cover material in the example calculations would not apply.

NOMENCLATURE

A	Cross-sectional area of interest in soil column (cm^2)
ABA	Absorption factor for inhaled contaminant
ABP	Absorption factor for a contaminant on particulate matter being inhaled
ABS	Absorption factor for dermally contacted contaminant
AI	Acceptable intake (mg/day)
BCF	Bioconcentration factor (L/kg)
BW	Body weight (kg)

C	Concentration of a contaminant in the vapor phase in soil pores ($\mu g/m^3$)
C_a	Ambient air concentration at exposure location ($\mu g/m^3$)
C_{as}	Contaminant concentration in air at the soil surface where emission occurs ($\mu g/m^3$)
C_F	Concentration of contaminant in fish (mg/kg)
C_L	Concentration of contaminant in leachate (mg/L)
C_m	Concentration of pollutant in meat (mg/kg)
C_o	Initial concentration of contaminant in soil (mg/kg)
C_p	Concentration of contaminant in particulates being inhaled ($\mu g/m^3$)
CR	Dermal contact rate of soil (g/day)
C_s	Concentration of contaminant in soil (mg/kg [=$\mu g/g$])
C_{sm}	Contaminant concentration in sol corresponding to vapor saturation (mg/kg [=ppm])
C_w	Concentration of contaminant in water (mg/L)
D_{ei}	Effective diffusivity (cm^2/s) ($=D_i \varepsilon^{1/3}$)
D_i	Molecular diffusivity (cm^2/s)
D	Air dilution factor ($=C_a/C_{as}$)
F	Correction factor for changing body weight when AI is based on 70 kg BW and soil ingestion lasts only during childhood as compared to lifetime; for soil ingestion during ages 1 through 5, F = 0.323
f_g	Functional relationship defining fate and transport of contaminants in leachate to groundwater
GI	Absorption rate in gastrointestinal tract
H	Henry's Law constant ($atm \cdot m^3/mol$)
IH	Daily inhalation of air (m^3/day)
IF	Daily fish consumption (kg/day)
IM	Daily meat consumption (kg/day)
IV	Daily vegetable consumption (kg/day)
IW	Daily water consumption (L/day)
IR	Daily ingestion rate of soil (g/day)

k	Biodegradation constant (L/day)
K_{as}	Soil-air partition coefficient (g soil/cm^3 air [=41H/K_d])
K_d	Soil-water partition coefficient (cm^3 water/g soil)
K_{LS}	= C_s/C_L
K_{sv}	= C_v/C_s
K_{vm}	= C_m/C_v
LS	Width dimension of contaminated area perpendicular to wind direction
LT	Exposure time over a lifetime (70 years) (days)
MH	Mixing height (m)
N_A	Emission rate ($\mu g/cm^2 \cdot s$)
$\overline{N}_A$	Average emission rate ($\mu g/cm^2 \cdot s$)
POT	Potency slope factor $(mg/kg \cdot day)^{-1}$
Q	Total emission rate ($\mu g/s$)
SL	Safe levels for noncancer effects (mg/kg·day)
SM	Exposure frequency over a lifetime
t	Time (s)
z	Depth measured from the soil-air interface (cm)
V	Average wind speed within mixing zone = (0.5) wind speed at the mixing height (m/s)

Greek Letters

ϵ	Porosity
$\bar{\rho}_s$	Bulk density of soil (g/cm^3)
ρ_s	True density of soil (g/cm^3)

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